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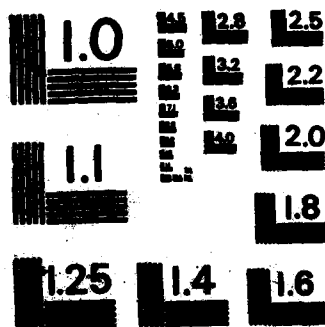
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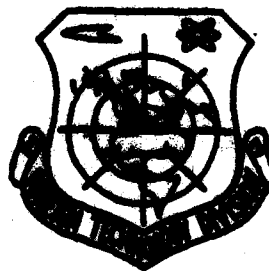
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PROBLEMS RELATED TO PLASMA IN HIGH SPEED FLIGHT

by

Wu Chengkang



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Problems Related to Plasma in High Speed Flight

by Wu Chengkang
(Mechanics Institute, Chinese Academy of Sciences)

When long range ballistic guided missiles and earth satellites, space shuttles or planetary probes enter the atmosphere, because of extremely high flight speed they attract the high temperature heating of the surrounding gas and form local ion plasma. This has a very large effect on the spacecraft's structural reliability, heat transfer, radio communications and the physical phenomena produced in flight. High performance spacecraft require a long life, small thrust and a very high specific impulse propulsion system. For this reason, new electric propulsion methods such as electrothermal propulsion, ion propulsion and plasma propulsion have been developed. This paper briefly introduces problems in three areas: the high temperature heat transfer of plasma in high speed flight, the effects of the plasma sheath in high speed flight on electromagnetic waves and the high specific impulse electric propulsion method.

I. The Problem of the High Temperature Heat Transfer of Plasma in High Speed Flight

1. Heat Environment

When a high speed aircraft enters the atmosphere, the gas ahead is acutely compressed by the aircraft, the surrounding gases and aircraft walls produce violent friction and the gas temperature rises to 7,000 or 8,000 degrees or even over 10,000 degrees forming partial ionization plasma. Because the physical shapes, speeds, altitudes and times of orbit of different aircraft are different, the parameters of the produced

plasma can be very different from the environment heating the aircraft. Basically, the heat environment of high performance ballistic guided missiles and manned airships are of two different types.

In order for intercontinental ballistic missiles to accelerate for attack and increase accuracy, a small headed long slender shape with low drag and large angle re-entry are used. It falls to an altitude of ten odd kilometers within 20 or 30 seconds and the speed is still above 5 kilometers/second. The special features of plasma are high pressure, high temperature, it belongs to a continuous medium and it is in or close to thermal balance. Convection heating is primarily used for aircraft heating; the heat flow is large, the shearing force is large and the time is short.

Because the winged soaring spacecraft is manned and needs to be used many times, small angle re-entry is used and at a high altitude for a long time there is deceleration. For this reason, the characteristics of plasma are low pressure, high temperature, imbalance and flow from the free molecules to the transient region to within the continuous medium. Convection heating is primarily used for aircraft heating; the heat flow is small, shearing force small and the time is long.

Ballistic type satellite re-entry lies between the two above mentioned situations yet is closer to the later. This is especially the case for manned spacecraft. When the Apollo airship returned from the moon to earth, its speed was relatively high and the radiation portion in the heating could not be overlooked.

When a detector enters the planetary atmosphere, the temperature of the produced plasma is high because the flight

speed is high. Radiation is primarily used for aircraft heating and convection is also important. The specific parameters and special features are determined by the planetary atmosphere's components and parameters, the planetary mass and the parameters of the flight orbit.

The representative parameters in the problems of plasma heating in high speed flight are gas parameters h_s , T_s and p_s (enthalpy, temperature and pressure intensity) of the stationary points in front of the aircraft, heating rates q_s and q_{\max} (stationary points and maximum heat flow) for the aircraft and shearing force τ_{\max} (maximum shearing stress). When high speed aircraft enter the atmosphere, the typical orbital and stationary point gas flow parameters are as shown in figures 1-4.

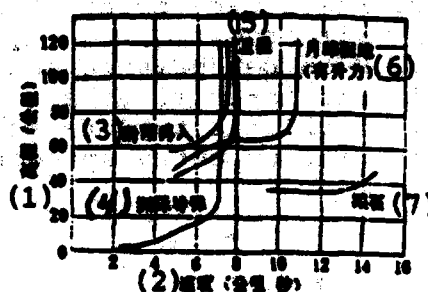


Fig. 1 Typical Orbits of Several Types of Aircraft Re-entering the Atmosphere

- Key:
1. Altitude (kilometers)
 2. Speed (kilometers/second)
 3. Soaring re-entry
 4. Intercontinental ballistic missile
 5. Satellite
 6. Returning to earth from the moon (with lift)
 7. Aerolite

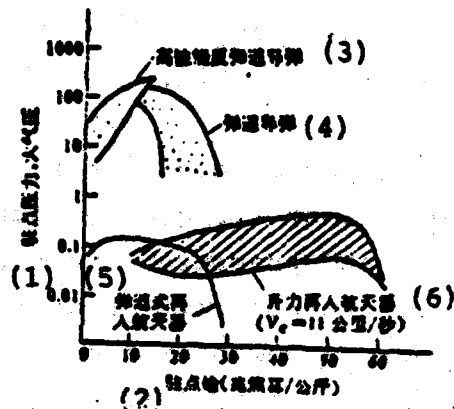


Fig. 2 Typical Stationary Point Parameters of Several Types of Aircraft Re-entering the Atmosphere

- Key: 1. Stationary point pressure, atmospheric pressure
 2. Stationary point enthalpy (megajoule kilogram)
 3. High performance anti-ballistic missile
 4. Ballistic missile
 5. Ballistic type re-entry spacecraft
 6. Lift re-entry spacecraft

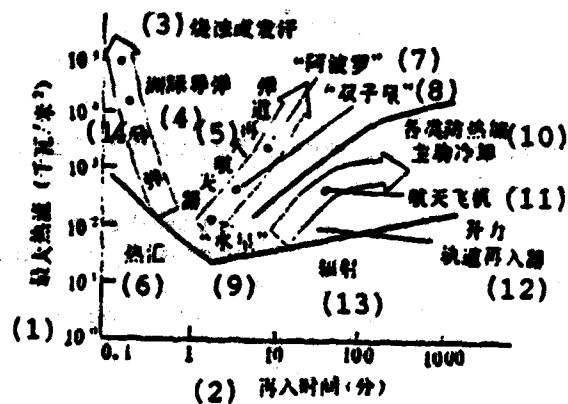


Fig. 3

Fig. 3 Re-entry Time and Maximum Heat Flow of Several Types of Aircraft Re-entering the Atmosphere

- Key: 1. Maximum heat flow (kilowatts/meter²)
 2. Re-entry time (minutes)
 3. Ablation or diaphoresis
 4. Intercontinental guided missile
 5. Ballistic re-entry spacecraft
 6. Heat sink
 7. "Apollo"
 8. "Duplex Star"
 9. Mercury
 10. Various types of anti-heating drive cooling
 11. Spacecraft
 12. Re-entry vehicle
 13. Radiation
 14. Guided missile

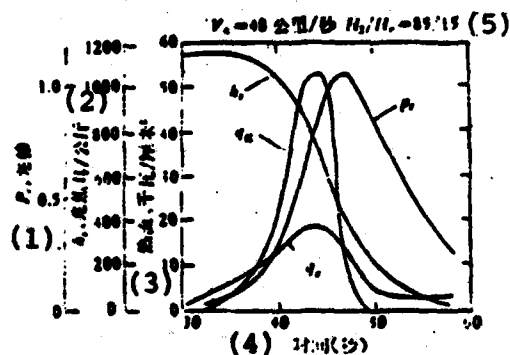


Fig. 4 Environmental Parameters of Flying Vehicles Entering the Atmosphere of Jupiter

- Key: 1. P, Pascal
 2. Megajoule/kilogram
 3. Heat flow, kilowatts/centimeter²
 4. Time (seconds)
 5. Kilometers/second

The heating of the gas on the surface is greatly influenced by the roughness of the wall surface, the material of the entering gas boundary layer, the existence of solid particles in the flow field and the turning of the laminar flow to turbulent flow. When there is radiation heating, the gas

radiation quality, absorption of the solid and reflection quality are all very important. These problems are all topics being researched.

2. Heat Proof Measures

Because of aerodynamic heating, it is necessary to adopt heat proof measures. Many heat proof methods have been proposed and tested such as metallic heat sink, radiation heat dissipation, ablation heat proofing, diaphoresis cooling and even the use of magnetic fields to separate the plasma from the surface of the material. However, after many years of practice, the most advanced heat proof measure under a high flow is the ablation method. We can use the ablation-radiation method under a low heat flow. Diaphoresis cooling has always been in the stage of research. Only theoretical investigations have been done on the magnetic field method, yet because it is difficult to realize, further work has not been done.

The two different types of heat environments require different heat proof systems. Guided missile types primarily use ablation capabilities and the spacecraft types primarily use heat insulation capabilities. Yet, when referring to each specific flying vehicle, because the heating environments and task requirements of each part are different, the decision of which heat proof system is to be used is painstaking work and what new materials, technology and structures are being continually researched to meet the various requirements.

3. The Calculation of Ablation Heat Proofing and Simulated Tests

Theoretical analysis calculations, ground simulation tests and flight tests are three major methods for studying and resolving the problems of aerodynamic heat in high speed flight. They are mutually supporting and complementary. After a great

deal of research work, the ablation process of high temperature gas flow on the wall surface's heat transfer and ablation materials has become clear in principle and can be calculated. Calculations include chemical reactions, calculation of the massively inserted high temperature gas flow boundary layer, the heat conduction and chemical changes in the solid material, decomposed gas produced and the used solid flow, the melting of wall surface materials as well as the flow and evaporation. Much research has been done abroad on the particulars of the process and they have drawn up complex computing programs for computing the results of most situations. However, there are also complex situations such as the surface producing slot patterns, mechanical corrosion of the solid, local complex shapes, new materials, unclear ablation mechanisms and physical data which make it difficult to carry out accurate computations. More advanced computation methods require test proof and the production and technical structures also require examination and testing. Thus, simulation tests are an important stage in the study of heating and heat-proofing in high speed flight.

When dealing with the problem of heating in high speed flight it is impossible to totally repeat the flight conditions or create the exact same test conditions. We can only use approximately or partially similar tests. The test results and theoretical analysis are combined and the test results of each part are synthesized in order to resolve the problems. To research the hydrodynamic phenomena, tests in a wind tunnel with low temperature materials can be carried out and to research high temperature gas flow heat transfer we can carry out shock wave tests. Yet, to test the actually used high temperature heat proof material and structure, we must have high temperature gas flow for a long time (calculated in seconds or minutes). The arc heating plasma generator and combustion gas flow test unit are the two types most often used. The combustion

gas flow device is mainly used to test the large sized structure and to study the changes of the contour. Its gas flow temperature is quite lacking as compared to the real situation. The continuous type test equipment which truly produces gas temperature close to actual flight is the arc heater.

The arc heating gas flow began to be used at the end of the 1950's to study the problem of heating in high speed flight. Various types of heaters were tested for many years and those shown in fig. 5 are only a small number of them. Many types of electromagnetic acceleration devices were also tested.

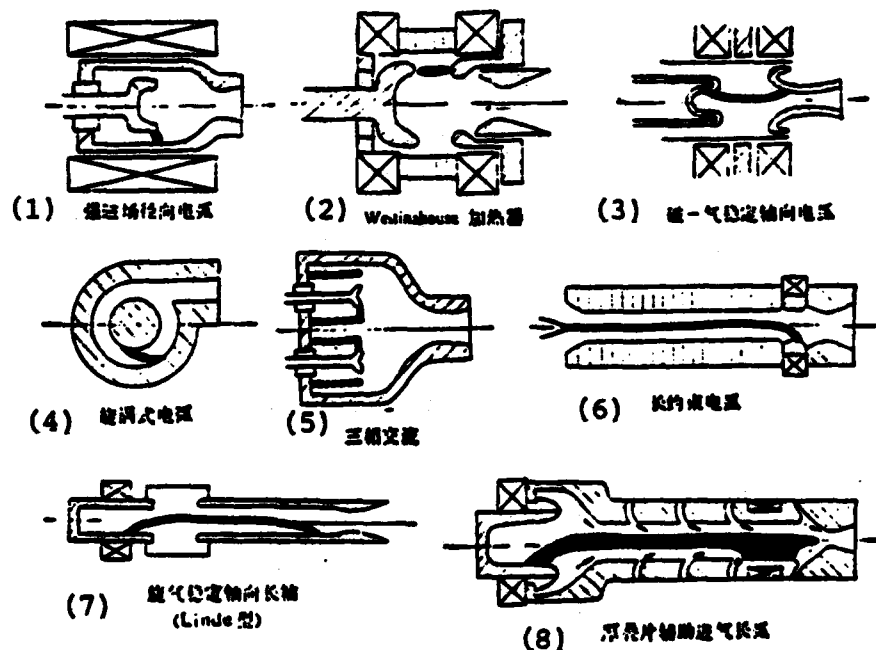


Fig. 5 Various Types of Arc Heaters

- Key: 1. Strong magnetic field radial arc
2. Westinghouse heater
3. Magnetic-gas stable axial arc
4. Vortex arc

- Key: 5. Three phase cross flow
6. Long binding arc
7. Revolving gas stable axial long axle
(Linde model)
8. Thick stack auxiliary gas intake long
arc

The electromagnetic and electric flow action of a Lorentz force is used to produce a high speed, high enthalpy gas flow. However, after twenty years of development, a heater with high power, direct current and a long arc has been developed as the enthalpy device of the aerodynamic heat simulation test equipment. Because of the electromagnetic accelerator's complexity and its tendency to synthesize the partial tests and theoretical analysis calculations, there has been no further development.

Generally, a heater with small power and a low enthalpy value use a spray gun form. Yet, the parameters must be made very stable, the electrodes must have a long life-time, pollution must be small, it must adapt to various working gases and various moving parameter ranges. It is also lacking in serialized advanced designs which is especially the case in China. Because high powered heaters do not easily resolve the problems caused by a large electric current but combine with the complexity of the heater as well as the drawbacks of the alternating current heater in arc stability and parameter range, the present tendency is to use a single direct current heater with high voltage (reaching 50,000 volts) and medium electric current ($\leq 2,000$ amperes). The type of heater used at the end of the 1960's tended to be a stack wall stable long arc with low pressure, high enthalpy and small current and a revolving gas stable long arc with high pressure, medium enthalpy and a large current. Yet, they still had shortcomings in performance. Two types of combined heaters were developed during the 1970's which used a thicker stack to maintain the

arc length and revolving as was sent into the stack to protect the linked arc. We can use various types of test forms based on the requirements for simulating the different heat environments. For example, subsonic efflux, supersonic efflux, casing, supersonic wind tunnel etc. Recently, because of the requirements of the Jupiter probe to enter the atmosphere of Jupiter, high temperature radiation heat transfer was used to test the arc column part of the model placed in the long arc.

Relatively good results have been obtained in calculating the performance of the arc heater in a long arc wall stable model. However, for other even more complex heaters, direct calculations have still not been developed. By using similar criterion, we can extrapolate the performances of certain types of heaters yet success has still to be achieved.

4. Brief Summary

The technical problems of the aerodynamic heating of most guided missiles and airships entering the atmosphere have been resolved abroad. Yet, research on the problems related to high performance warheads, new materials, even finer mechanism, more reliable simulation test methods and entering planetary atmospheres are not as extensive as past research work and development. However, much work is still being carried out.

II. Problems of the Plasma Sheath in High Speed Flight

1. Nature of the Problem and Plasma Sheath Parameters

The so-called plasma sheath is a high temperature ion gas produced in high speed flight, especially the free electrons which form a sleeve layer on the outer surface of the aircraft. It obstructs radio communications and at the same time forms an electrified trail observable by radar waves. The plasma sheath causes the electromagnetic waves between the aircraft

and outer boundary to transmit serious attenuation or suspension thus causing the speech communications of the manned spacecraft, the aircraft's parameter real time telemetering, the control of guided missiles and electronic resistance not to be able to function normally. Furthermore, this is often the most crucial immediate occurrence in the flight process. From the scattering of the electrified trail to the radar waves, we can differentiate certain characteristics of the aircraft which have great significance for the tracking of aircraft. In order to improve external communications, it is necessary to resolve the problem of transmitting electromagnetic waves by the plasma sheath. In order to use the trail's electric properties for assault protection or anti-assault protection it is necessary to clarify the trail properties and the factors influencing these properties.

The parameters of the plasma sheath are primarily the electron density distribution and secondly the electron collision frequency and electron temperature. These are primarily determined by the flight temperature, speed and body form. An aircraft with a large nose (such as the Apollo manned spacecraft) has gas ionization primarily produced in a nose area with intense shock wave non-viscous flow which flows into the rear flow field after expansion. The electrons of the long slender sharp nose primarily appear in the boundary layer. The long slender blunt nose is in various flight altitudes (Reynolds number) and so the contributions of the two are different. When the Reynolds number is high, the electrons are primarily from the entropic layer and medium Reynolds numbers (over 40 kilometers) have an equal contribution by the boundary layer and entropic layer. With low Reynolds numbers (over 70 kilometers) the viscosity effect wave and entire shock wave layer are different according to the altitude and the chemical reaction transforms from a balanced to an unbalanced and

congealed flow. Fig. 6 shows the parametric distribution of a typical plasma sheath.

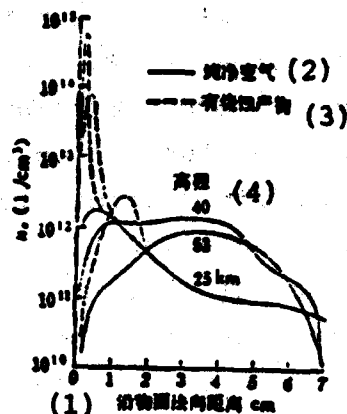


Fig. 6 Density Distribution of Electrons on the Side of the RAM-C Warhead

Key: 1. Normal distance along surface cm
 2. Pure air
 3. Product with ablation
 4. High range

Aside from the flight parameters, the substances sprayed from the surface such as ablation products or electron attracting substances can produce noticeable effects on ionization. For example, substances with potassium and sodium increase the electrons and substances with fluorine decrease the electrons.

Calculation of the plasma parameters is mainly the calculation of the various chemical reactions including the ionization reaction placed in the flow field, that is, the gas composition changes with the flow field. When the Reynolds number is high, we can use the stream tube method. It is based on the known non-viscous flow field pressure distribution and uses the stream tube one dimensional flow to study the effects of the chemical reactions. There are also several methods for calculating the

boundary layer. For medium and small Reynolds numbers ($Re > 10^2$ equal to a 80-30 kilometer altitude) use the simplified Navier-Stokes equation to solve the flow field. For smaller Reynolds numbers we must use a method to directly solve the N-S equation. Theoretical analysis work also requires the study of the separation of the flow field, the effects of the vortex flow on the electron density, the effects of the ablation products, the effects of the sprayed substances on the electrons and the effects of the chemical reaction constants.

For the measurement of the plasma sheath parameters in flight, foreign nations have used waveguide antenna measurements, static electricity probes, radio frequency conductance probes, electronic sound probes, resistance line probes, microwave radiometers and isolated slit antennas. At present, the measurement methods are still in the development stage. On the basis of the sensor, laboratory tests and data analysis have made the missile carrying of sensors convenient and reliable, and the cost is lower.

2. The Effects of the Plasma Sheath on Electromagnetic Waves.

Electromagnetic waves are complex when transmitted in plasma which is not uniform and has boundaries. To specifically analyze the phenomena which occur on the aircraft, we consider that the electromagnetic waves go through a uniform layer, the thickness is known and there is plasma with unlimited area (one dimensional propagation). Based on an approximate analysis, we know that the relationship of electromagnetic frequency

ω_p is crucial. $\omega_p \approx \sqrt{n_e e^2 / \epsilon_0 m_e}$. In this formula, n_e is the density of the electrons, e and m_e are the electron's charge and mass, ϵ_0 is the vacuum's dielectric constant. For simple situations wherein there is no collision between the electrons and other particles we can find that when $\omega \gg \omega_p$, the

electromagnetic waves can pass through the plasma without attenuation. When $\omega < \omega_p$, the transmitted waves inside the plasma will attenuate and the waves reflected from the outside surface toward the plasma will totally reflect on the boundary. The situation is more complex for plasma with collision. However, when there is relatively low collision frequency ($\nu < \omega_p$), there is not a large difference between this situation and that of not having collision.

We can find the plasma parameters from the effects of the plasma sheath on the electromagnetic waves. Thus, the attenuation and phase shifts of the electromagnetic waves can be measured by the plasma parameters which is also called "plasma diagnosis."

3. Resolving the Plasma Path Obstructing Communications

After testing various measures such as raising power and increasing the magnetic field, a still more hopeful method is the raising of the electromagnetic wave frequency and spraying electrophilic substances to decrease the electron density of the local plasma sheath.

We can see from the relationship of ω_p and n_e that for a electron density of $n_e \approx 10^{12}/\text{cm}^3$, the corresponding plasma frequency is 10GHz. If the communication frequency used is higher than 10GHz, that is, uses micrometer waves, the problem of the plasma sheath in most ballistic missile antenna positions can be overcome. Millimeter wave frequencies are higher than most existing communication systems yet they can be totally realized technically.

The method of spraying electrophilic substances causes the electrons and electrophilic substances to combine and form negative ions. This decreases the free electron density as well

as the plasma frequency so that the communication frequency is higher than ω_p and lightens the attenuation of the electromagnetic waves in the transmission.

The most effective electrophilic substances are fluids. When sprayed from the upstream on the antenna into the flow field, this can have a certain penetration depth and because the speed is lower than the flow field gas, it can remain for a relatively long time in the flow field. Because of the aerodynamic breaking (low altitude) and evaporation breaking (high altitude) in the flow field, a large number of finely broken liquid drops are produced forming a third substance of electrons and ions on its surface. An excessive amount of electrons causes the particles of the liquid drop surface to transform into negative ions. When the negative ions evaporate the latent heat is lower than the neutral molecules and thus is even easier to evaporate. Therefore, the liquid spray can effectively absorb the electrons and decrease the local area's electron density. Aside from this, when there is liquid evaporation there is heat absorption causing a drop in the local temperature. This also causes the electron density to decrease which is beneficial for the transmission of electromagnetic waves.

The very crucial problem is the spraying method and quantity. For example, how to use the minimum amount of water to obtain optimal results for improving communications is a problem worthy of research.

In ground tests and research on plasma sheaths we can use an arc heated wind tunnel or use a plasma generator in a common wind tunnel to produce plasma. The use of the ballistic targets is very suitable for ion trail research. Electric probes are simple and reliable probing instruments for ground tests.

Microwave measurements can provide certain parameters of the plasma, yet detailed parameter distributions must be obtained and the required microwave equipment is very complex.

Because of the limitations of the ground test simulated plasma, the actual fixed quantity tests often must rely on flight tests for completion. The plasma target flight test RAM plan publicly announced by the United States was divided into three series (A,B,C) between 1961 and 1970. There were a total of 8 launches and besides one failure, plasma target data was obtained by various probes. The Trailblazer plan was divided into two stages. Beginning in 1966 until 1973 there were 9 launches. We can see from this the serious attention given abroad to the problem of plasma targets.

4. Brief Summary

The problem of plasma targets is one of the crucial problems in guided missile and space technology. After over 10 years of active research by foreign nations many problems have been clarified in principle yet many details still await further research. There are possibly ways of actually resolving the problems but applicable plans are still being kept secret.

III. Problems of Electric Propulsion in Space

Since the 1950's, foreign nations have carried out a great deal of research on electric propulsion and have developed over ten different types of electric thrusters. Among these, several types have already been used successfully in space. International conferences are being convened continually. Electric thrusters with high specific impulse, low thrust, long life, high precision and good reliability have been used in various types of satellites, space stations for the attitude control of space probes, maintaining position and correcting orbits as

well as for the main propulsion for future interplanetary flight. The basic principle of electric propulsion is the use of various electrical and magnetic effects to accelerate the propulsion working substance to a jet speed which can far exceed chemical fuel combustion. As a result, a very high specific impulse can be attained - the impulse which can be produced by each kilogram of sprayed working substance for the airship (the product of the thrust and operating time). At present, the successfully developed electric propulsion system can be divided into three major categories: electrothermal, static electric and electromagnetic. Below we will introduce these three types of electric thrusters individually.

1. The Electrothermal Thruster

The electrothermal thruster is a simple and improved cold gas thruster. It uses a resistance component or arc discharge as the heat source and by increasing the entropic value of the working substance the exhaust speed can be raised. There are two types, the stable and the pulsed. The working substance can be hydrogen, nitrogen, ammonia, hydrazine etc. Early research used an arc heating working substance and reached a relatively high specific impulse. A hydrogen working substance was used but has not yet been tested in flight. The resistance heating type thruster has been used in satellites. In 1968, the resistance heating ammonia thruster was used in a satellite. The thrust was 222 millinewton, the specific impulse was 135 seconds, the power was 11 watts and it was used in the satellite's attitude control. We can see that the specific impulse of this type of thruster was not high (naturally it must be higher than cold gas), yet use was convenient. In the last several years, there has been much research done on the electrothermal hydrazine thruster. This type of thruster uses electric heating to cause the hydrazine to reach a temperature of chemical decomposition so that reliability is increased and the specific

impulse is raised. The attained performance was 320 millinewton and a life of 100 hours. The plan used an electrothermal hydrazine thruster to maintain the north-south position of a communication satellite. The major advantages of the electrothermal thruster are that its structure is simple, it is flexible in application and it is pulse operating. Its shortcomings are that temperature is limited, exhaust speed is less than 10^4 meters/second and its life is not long enough.

2. The Static Electric Thruster

The static electric thruster uses an electric field to accelerate ions and thus produces a device with thrust. Its major components are the ion generator, accelerated electric field and electron neutralizer. The working substance in the ion generator (liquid cesium or silver, inert gas can also be used) is evaporated in the evaporator by the supply system, enters the discharge room and in the cylindrical discharge room, the electrons emitted from the cathode, under the action of the radial electric field and longitudinal magnetic field, coil around the magnetic line of force to carry out a spiral movement. They collide with the atoms of the working substance to form ions. Downstream of the discharge room there is an anodo-screening grid. Its electric potential is the same as that of the main cathode potential. The acceleration pole is installed less than one millimeter downstream from the anodo-screening grid. The potential is negative which causes the ions to accelerate the spray. The neutralizer supplies electrons in the area of the outlet causing the sprayed jet flow to be electrically neutral. See. fig. 7 for the principle of the static electric thruster.

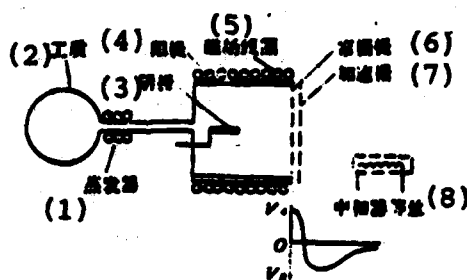


Fig. 7 Schematic of the Electron Bombardment Type Static Electric Thruster

- Key: 1. Evaporator
 2. Working substance
 3. Cathode
 4. Anode
 5. Magnetic field coil
 6. Anode-screening grid
 7. Accelerating grid
 8. Neutralizer isoline

At present, the NASA center in the United States has developed a 30 cm diameter thruster to be used for interplanetary flight and orbiting and an 8 cm diameter thruster which synchronizes and holds the north-south position. The 30 cm diameter thruster has a thrust of 135 millinewton, specific impulse of 3,000 seconds and total power of 2,700 watts. The 8 cm diameter thruster has a thrust of 10 millinewton and specific impulse of 3,000 seconds. The life-time is required to exceed 20,000 hours. It can be seen that the ion thruster is a thruster with really high specific impulse.

After many years of tests and research on the static electric thruster, including space endurance tests, it is at present still in the prototype test stage. Mission analysis has been carried out on electric propulsion systems for use in

flight in the solar system. Aside from this, in recent years work has been done to investigate the principles of ion thrusters and the possibility of using the technology in industry. For example, the use of ion thrusters has been proposed for sputtering deposits, ion beam processing and surface treatment and to provide new technology, new components and new materials in industry, biology, medicine and materials science. This is a new movement worthy of attention. It also shows that a new item of technology must possess strong vitality and must seek application in many areas.

3. The Electromagnetic Thruster

The electromagnetic thruster uses the action of electromagnetic force to cause the plasma to accelerate the spraying and produce a device with thrust. There are three types: the steady state, the alternating plasma power arc jet (MPD) and pulsed plasma thruster (PPT). The MPD device can produce relatively large thrust and high specific impulse yet it is still in the laboratory stage. In recent years, a pulsed plasma thruster which uses solid fluon as the working substance has been developed rather quickly. Its working substance system is simple and it is suitable for zero gravity and vacuum environments. It uses an accumulating condenser for instantaneous current discharge and forms high temperature arc ablation and separates the working substance. After electromagnetic force and thermal force accelerate, the exhaust thrust is produced. This type of thruster was already installed in a synchronized satellite in 1968 to maintain the east-west position. See fig. 8 for its schematic.

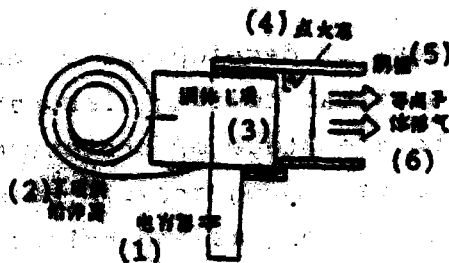


Fig. 8 Schematic of Solid Pulsed Plasma Thruster

- Key:**
1. Condenser
 2. Work substance's supply spring
 3. Solid working substance
 4. Igniter plug
 5. Cathode
 6. Plasma exhaust

The performance of the presently developed prototype are: unit impulse is 30.5 millinewton - seconds, average thrust is 4.5 millinewton, average specific impulse is 1,500 seconds and consumed energy is 135 watts. It has been shown that similar to this prototype, efficiency can reach 30% and that further research of an accelerating mechanism can improve its efficiency and performance. This type of thruster is suitable for use in various types of satellite attitudes which requires high precision and long life as well as for orbit control.

The technology of the plasma thruster is related to other important scientific technology. For example, research success on controllable thermonuclear reactions, high temperature plasma physics and high energy particle accelerators have a direct effect on the related technical problems of plasma accelerators. Moreover, research on plasma propulsion also has reference value for these sciences. The mutual influences between these scientific areas have been seen very clearly in the plasma

research work done in the Soviet Union.

4. Brief Summary

After over 20 years of development of electric propulsion technology, from theoretical testing, laboratory research has made the transition to the stage of prototype production and test use in space flights. Among these, the more advanced and mature thruster is the ion engine and pulsed plasma thruster. It has recently been used for the attitude and orbital control of various types of synchronized satellites and in the future will possibly be used for the orbital lift of satellites and the main propulsion for interplanetary flight. Related scientific research has a mutually promoting effect on other science and technology. For example, electric propulsion research is helpful for plasma physics, thin gas kinetics, vacuum discharge physics as well as related testing techniques. It also promotes the development of certain new materials, new technology and new techniques.

The problems of plasma in space technology involve a very broad area. These problems have already been well researched abroad and many of the problems have been resolved. However, at present there is not the "great demand" for the basic research in foreign nations. Yet, it appears that the work has not stopped and key problems are still kept secret. To coincide with China's actual needs, aside from resolving real problems, we should begin to thoroughly research the related scientific problems themselves. In this way, we must raise China's scientific and technological level in this area and promote the development of science and technology related to this for use on a large scale.